Distribution Network Expansion Planning with Optimal Siting and Sizing of Electric Vehicle Charging Stations

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***Abstract*- The investment of connecting charging stations into distribution networks should be considered in the optimal planning of charging stations for electric vehicles (EVs). This paper proposes a mathematical model for multistage distribution network expansion planning taking optimal siting and sizing of EV charging stations into account. In the proposed model, the capacity of existing substations can be increased, existing network feeders can be replaced with wider section feeders, new feeders and new charging stations can be built. Network security constraints are considered. A new constraint is formulated to guarantee the topology of the obtained distribution network is radial. Numerical results indicate that the proposed method can allocate charging capacity among candidate charging station sites optimally, and the total investment and operating cost of the distribution network is reduced.**

***Index Terms*—Charging Station, Distribution Network, Electric Vehicle, Expansion Planning, Mixed integer linear programming.**

I. Nomenclature

A. Binary Variables

$x_{j,t}^{RJ}$	Alternative RJ for replacing branch j at stage t
$x_{k,t}^{AK}$	Alternative AK for adding branch j at stage t
$x_{l,t}^{S0}$	Decision variable for adding or expanding substation l at stage t
$x_{l,t}^{SL}$	Capacity alternative SL for expanding substation l at stage t
$x_{p,t}^{C0}$	Decision variable for adding charging station p at stage t
$x_{p,t}^{expand}$	Decision variable for expanding charging station p at stage t
$\boldsymbol{x}_t$, $\boldsymbol{x}$	Vectors of decision variables at stage t and all stages, respectively
$y_{i,t}^{F}$	Utilization of existing branch i at stage t
$y_{j,t}^{R0}$	Utilization of alternative $R0$ for replacing branch j at stage t
$y_{j,t}^{RJ}$	Utilization of alternative RJ for replacing branch j at stage t
$y_{k,t}^{AK}$	Utilization of alternative AK for adding branch j at stage t
$\boldsymbol{y}_t$, $\boldsymbol{y}$	Vectors of branch utilization variables at stage t and all stages, respectively
$q_{i,t}$	Flag whether node i with load is connected at stage t

B. Continuous Variables

$f_{i,t}^{F}$, $f_{\max,i}^{F}$	Current and maximum allowable current of existing branch i at stage t
$f_{k,t}^{AK}$, $f_{\max,k}^{AK}$	Current of branch in the addition network at stage and its maximum capacity AK
$f_{j,t}^{R}, f_{\max,j}^{R0}, f_{\max,j}^{RJ}$	Current of branch in the replacement network at stage t and maximum capacities of $R0$ and RJ.
$\boldsymbol{f}_t^F, \boldsymbol{f}_t^R, \boldsymbol{f}_t^K$	Current vectors for the fixed, replaced, and added branches at stage t
$g_{l,t}^{S}, g_{\max,l}^{S}, g_{\max,l}^{SL}$	Power injection at node l at stage t and the substations' maximum capacity.
$\boldsymbol{g}_t$	Column vector of the nodal injection at stage t
$r_{m,t}$, $\boldsymbol{r}_t$	Load shedding of node m and vector of load shedding at stage t, respectively
$P_{p,t}$, $\boldsymbol{P}_t$	Load of charging station p at stage t and the vector for all the charging stations
$V_{l,t}, V_{m,t}, V_{p,t}$	Voltage magnitude of node l, m, p at stage t, respectively
$\boldsymbol{V}_t, \boldsymbol{V}_{\min}, \boldsymbol{V}_{\max}$	Column vectors of the nodal voltages at stage t and their minimum and maximum limits
$c_t^{inv}(\boldsymbol{x}_t, \boldsymbol{P}_t, \boldsymbol{P}_{t-1})$	Total investment at stage t
$c_t^{oper}(\boldsymbol{r}_t, \boldsymbol{y}_t, \boldsymbol{P}_t,)$	Total operational cost at stage t

C. Parameters

$x_{p,0}^{C0}$	Whether node p has a charging station at initial stage (binary variable)
$P_{p,0}$	The charging load at node p with a charging station
$d_{m,t}$, $\boldsymbol{d}_t$	Load of node m and all nodes at stage t
$P_{Demand,t}$	Total charging demand at stage t
T	Total number of planning stages
$C_p^{expand}, C_p^{variable}$	Fixed expansion cost and variable investment cost for charging station p
δ_t^{inv} , δ_t^{oper}	Present value factors for the investment and operational costs at stage t

II. Introduction

There are growing concerns over energy security and greenhouse gas emissions. Transportation electrification is considered as an important way to solve these concerns. More

and more electric vehicles (EVs) will therefore be integrated with electrical power systems through plug-in hybrid and electric vehicles. The integrations need charging facilities both at public and private places. The role of charging infrastructure is essential for the mass implementation of EVs as discussed in [1]. And the detailed requirements and conditions that should be considered for the design of charging infrastructure systems for EVs are also presented.

Although charging at home is the first choice for many EV owners living in their houses, many other EV users who don't have private parking places or garages will have to use public charging facilities. Huge investment will be needed to build public charging places in countries like China [2]. A multi-objective planning model for the layout of electric vehicle charging station is proposed in [3], which takes into account factors including charging consumers' behaviour, distribution of the charging demand, factors of municipal planning. Case studies are carried out based on the background of Chengdu City in China. A method is given in [4] to optimally locate and size charging station for EVs based on grid partition. Genetic algorithm is employed to minimize the EV consumers' distance to the charging facilities. In [5], mathematical programming formulation is formed to determine the best locations for building alternative transportation fuel stations. EV charging is considered.

To present, the work related to charging infrastructure planning mainly focuses on meeting charging demands with lowest investment costs and best users' convenience. The planning of charging locations doesn't consider the costs of connecting charging facilities to the grids. In this paper, the distribution network reinforcement planning is carried out simultaneously with the optimal siting and sizing of EV charging stations.

III. Mathematical Formulation

A. Problem Description

The distribution network expansion planning problem considered in this paper takes the following factors into account [6, 7]:

(1) the multistage planning problem has T stages with given duration;

(2) the distribution network includes existing feeders connecting to the upstream substation(s), candidate branches, existing and new load nodes, candidate and even existing nodes for charging station(s);

(3) to satisfy traditional load demands and future charging requirements, existing substation and charging station can be expanded, new substation and charging station can be added, and transfer capability can be increased by adding new lines or replacing conductors if necessary at any stage;

(4) the operational and maintenance costs are calculated with each branch.

B. Objective Function

The objective function for the integrated distribution network and charging station expansion planning includes two parts: the investment cost $c_t^{inv}(\boldsymbol{x}_t, \boldsymbol{P}_t, \boldsymbol{P}_{t-1})$ and the operational cost $c_t^{oper}(\boldsymbol{r}_t, \boldsymbol{y}_t, \boldsymbol{P}_t,)$. The objective function is as follows:

$$\min C(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{r}, \boldsymbol{P}) = \sum_{t=1}^{T} [\delta_t^{inv} c_t^{inv}(\boldsymbol{x}_t, \boldsymbol{P}_t, \boldsymbol{P}_{t-1}) + \delta_t^{oper} c_t^{oper}(\boldsymbol{r}_t, \boldsymbol{y}_t, \boldsymbol{P}_t,)] \tag{1}$$

The investment cost is determined at the beginning of each stage and is given by the cost of altering network branches (by changing cross-sections of existing feeder sections or by installing new feeder sections), network nodes (by increasing the capacity of existing substations or by installing new ones) and charging stations. The cost of operation is considered at the beginning of each stage period and corresponds to the annual operational and maintenance cost of network branches that are in use, to charging stations, and to power that is curtailed.

The total investment cost $c_t^{inv}(\boldsymbol{x}_t, \boldsymbol{P}_t, \boldsymbol{P}_{t-1})$ at stage t is the linear function of decision variable $\boldsymbol{x}_t$, charging power $\boldsymbol{P}_t$ and the charging power $\boldsymbol{P}_{t-1}$ (at stage t-1). It is calculated by

$$\begin{aligned} c_t^{inv}(\boldsymbol{x}_t, \boldsymbol{P}_t, \boldsymbol{P}_{t-1}) = \sum_{l \in \psi^S} (C_l^{S0} x_{l,t}^{S0} + \sum_{L \in \psi_l^S} C_l^{SL} x_{l,t}^{SL}) + \\ \sum_{j \in \psi^R} \sum_{J \in \psi_j^R} C_j^{RJ} x_{j,t}^{RJ} + \sum_{j \in \psi^A} \sum_{J \in \psi_k^A} C_k^{AK} x_{k,t}^{AK} + \\ + \sum_{p \in \psi^C} (C_{fixed}^p x_{p,t}^{C0} + C_p^{expand} x_{p,t}^{expand} + C_{vab}^p (P_{p,t} - P_{p,t-1})) \end{aligned} \tag{2}$$

The total investment $c_t^{inv}(\boldsymbol{x}_t, \boldsymbol{P}_t, \boldsymbol{P}_{t-1})$ at stage t includes the substation capacity expansion fixed cost ($C_l^{S0} x_{l,t}^{S0}$), and variable cost ($C_l^{SL} x_{l,t}^{SL}$) corresponding to choose candidate capacity of type SL, the capacity expansion cost of line j ($C_j^{RJ} x_{j,t}^{RJ}$) corresponding to choose candidate line type RJ, investment cost of building line k ($C_k^{AK} x_{k,t}^{AK}$) using line type AK, the fixed cost of building or expanding charging station at node p ($C_{fixed}^p x_{p,t}^{C0}$, $C_p^{expand} x_{p,t}^{expand}$, respectively), and the variable cost of charging station investment ($C_{vab}^p (P_{p,t} - P_{p,t-1})$), which is proportional to the added charging capacity $P_{p,t} - P_{p,t-1}$.

The total operational cost $c_t^{oper}(\boldsymbol{r}_t, \boldsymbol{y}_t, \boldsymbol{P}_t,)$ at stage t is the linear function of $\boldsymbol{y}_t$, charging station power $\boldsymbol{P}_t$ and curtailed load power $\boldsymbol{r}_t$. It is calculated by the following function and the meaning of each part at the right side of equation is obvious.

$$\begin{aligned} c_t^{oper}(\boldsymbol{r}_t, \boldsymbol{y}_t, \boldsymbol{P}_t) = \sum_{i \in \psi^F} O_i^F y_{i,t}^F + \sum_{j \in \psi^R} (O_j^{R0} y_{j,t}^{R0} + \sum_{J \in \psi_j^R} O_j^{RJ} y_{j,t}^{RJ}) \\ + \sum_{k \in \psi^A} \sum_{l \in \psi_i^A} O_k^{AK} y_{k,t}^{AK} + \sum_{p \in \psi^C} O^P P_{p,t} + \sum_{m \in \psi^D} C_m^D r_{m,t} \end{aligned} \tag{3}$$

C. Constraints

The following constraints are considered:

(1) Kirchhoff's laws, including KCL and Kirchhoff's voltages law (KVL). To obtain linear KVL constraints, the big number M is introduced to form the disjunctive version that is widely used in transmission expansion planning. The derivation of KVL can be found in [6].

$$\boldsymbol{S}^F \boldsymbol{f}_t^F + \boldsymbol{S}^R \boldsymbol{f}_t^R + \boldsymbol{S}^A \boldsymbol{f}_t^K + \boldsymbol{r}_t + \boldsymbol{g}_t = \boldsymbol{d}_t + \boldsymbol{P}_t \quad \forall t \in 1,\cdots,T \quad (4)$$

$$| Z_i^F f_{i,t}^F + \left[\boldsymbol{S}^F\right]_{rowi}^T \boldsymbol{V}_t | \le M(1-y_{i,t}^F) \quad \left\{i \in \psi^F, t \in 1,\cdots,T\right\} \quad (5)$$

$$| Z_j^{R0} f_{j,t}^{R0} + \left[\boldsymbol{S}^R\right]_{rowj}^T \boldsymbol{V}_t | \le M(1-y_{j,t}^{R0}) \quad \left\{j \in \psi^R, t \in 1,\cdots T\right\} \quad (6)$$

$$| Z_j^{RJ} f_{j,t}^{RJ} + \left[\boldsymbol{S}^R\right]_{rowj}^T \boldsymbol{V}_t | \le M(1-y_{j,t}^{RJ}) \quad \left\{j \in \psi^R, J \in \psi_j^{RJ}, t \in 1,\cdots T.\right\} \quad (7)$$

$$| Z_k^{AK} f_{k,t}^{AK} + \left[\boldsymbol{S}^A\right]_{rowk}^T \boldsymbol{V}_t | \le M(1-y_{k,t}^{AK}) \quad \left\{k \in \psi^A, K \in \psi_k^A, t \in 1,\cdots T.\right\} \quad (8)$$

(2) Operational limits

- The constraints of maximum branch flow

$$| f_{i,t}^F | \le y_{i,t}^{FI} f_{\max,i}^{FI} \left\{\forall i \in \psi^F, t \in 1,\cdots T.\right\} \quad (9)$$

$$| f_{j,t}^R | \le y_{j,t}^{R0} f_{\max,j}^{R0} + \sum_{J \in \psi_j^R} y_{j,t}^{RJ} f_{\max,j}^{RJ} \left\{\forall j \in \psi^R, t \in 1,\cdots T.\right\} \quad (10)$$

$$| f_{k,t}^A | \le \sum_{K \in \psi_k^A} y_{k,t}^{AK} f_{\max,k}^{AK} \left\{\forall k \in \psi^A, t \in 1,\cdots T.\right\} \quad (11)$$

- Constraints of substation capacity

$$0 \le g_l^S \le g_{\max,l}^S + \sum_{L \in \psi_l^S} (\sum_{\tau=1}^{t} x_{l,\tau}^{SL}) g_{\max,l}^{SL} \quad \left\{\forall l \in \psi^S, t \in 1,\cdots T.\right\} \quad (12)$$

- Nodal voltage limits

$$V_{\min,l} \le V_{l,t} \le V_{\max,l} \quad \{\forall l \in \psi^S, t \in 1,\cdots T.\} \quad (13)$$

$$V_{\min,m} \le V_{m,t} \le V_{\max,m} \quad \{\forall m \in \psi^D, t \in 1,\cdots T.\} \quad (14)$$

$$V_{\min,p} \le V_{p,t} \le V_{\max,p} \quad \{\forall p \in \psi^C, t \in 1,\cdots T.\} \quad (15)$$

(3) Load shedding limits

$$0 \le r_{m,t} \le d_{m,t} \quad \{\forall m \in \psi^D, t \in 1,\cdots T.\} \quad (16)$$

(4) Charging station capacity limits, which set the limits of charging station capacity and total charging requirement.

$$\sum_{p \in \psi^C} P_p \ge P_{Demand,t} \quad t \in 1,\cdots T. \quad (17)$$

$$P_{\min,p} \le P_{p,t} \le P_{\max,p} \quad \left\{\forall p \in \psi^C, t \in 1,\cdots T.\right\} \quad (18)$$

(5) Logic constraints, including all the logic constraints associated with decision variables.

For each line that is candidate for replacement, only one type of conductor can be selected at all stages:

$$\sum_{t=1}^{T} \sum_{J \in \psi_j^R} x_{j,t}^{RJ} \le 1 \left\{\forall j \in \psi^R\right\} \quad (19)$$

For each candidate line for addition, one type of conductor can be chosen at all stages:

$$\sum_{t=1}^{T} \sum_{K \in \psi_k^A} x_{k,t}^{AK} \le 1 \left\{\forall k \in \psi^A\right\} \quad (20)$$

At any stage, only one capacity can be selected for substation expansion

$$\sum_{L \in \psi_l^S} x_{l,t}^{SL} \le 1 \quad \left\{\forall l \in \psi^S, t \in 1,\cdots T.\right\} \quad (21)$$

No investment cost will occur if no candidate capacity is chosen:

$$\sum_{L \in \psi_l^S} x_{l,t}^{SL} \le x_{l,t}^{S0} \left\{\forall l \in \psi^S, t \in 1,\cdots T.\right\} \quad (22)$$

For a line that can be replaced, only the selected conductor type can be used and operational costs will arise. If no candidate conductor is selected, the existing conductor will be used and result in operational costs.

$$y_{j,t}^{RJ} \le x_{j,t}^{RJ} \left\{\forall j \in \psi^R, J \in \psi_j^R, t \in 1,\cdots T.\right\} \quad (23)$$

$$y_{j,t}^{R0} \le 1 - \sum_{j \in \psi_j^R} x_{j,t}^{RJ} \left\{\forall j \in \psi^R, t \in 1,\cdots T.\right\} \quad (24)$$

At any stage t, only the selected conductor type can be used and operational costs will arise for the candidate new lines.

$$y_{k,t}^{AK} \le x_{k,t}^{AK} \left\{\forall k \in \psi^A, K \in \psi_k^A, t \in 1,\cdots T.\right\} \quad (25)$$

If no charge capacity is added to the node p without charging facility at the initial stage, the charge capacity at this node should be equal to zero.

$$| P_{p,t} | \le M \sum_{\tau=0}^{t} x_{p,\tau}^{C0}, \left\{\forall p \in \psi^C, t \in 1,\cdots T.\right\} \quad (26)$$

For any charging node, the charging station can only be built once. If charging station is already there at the initial stage, the corresponding decision variable should be equal to 0 at all the stages.

$$\sum_{t=0}^{T} x_{p,t}^{C0} \le 1 \left\{\forall p \in \psi^C\right\} \quad (27)$$

For a charging node p, building and expansion of the charging station cannot occur simultaneously.

$$x_{p,t}^{expand} + x_{p,t}^{C0} \le 1 \left\{\forall p \in \psi^C, t \in 1,\cdots T.\right\} \quad (28)$$

At stage t, expansion is allowed when a charging station has been built:

$$x_{p,t}^{expand} \le \sum_{\tau=0}^{t-1} x_{p,\tau}^{C0} \left\{\forall p \in \psi^C, t \in 1,\cdots T.\right\} \quad (29),$$

where the $x_{p,\tau}^{C0}$ means if a charging station exists at initial stage when $\tau = 0$.

The capacity of the charging station is non-decreasing.

$$0 \le P_{p,t} - P_{p,t-1} \le M(x_{p,t}^{C0} + x_{p,t}^{expand}) \left\{\forall p \in \psi^C, t \in 1,\cdots T.\right\} \quad (30)$$

(5) Radial structure of distribution network. Improvements are made based on the work presented in [6] and the following constraints are derived.

$$\sum_{j \in \psi_i} y_{ij,t} \le M q_{i,t} \quad \forall t \in 1,\cdots T \quad (31)$$

$$q_{i,t} \le \sum_{j\in\psi_i} y_{ij,t} \quad \forall t\in 1,\cdots T \tag{32}$$

$$\sum_{k\in\psi^A}\sum_{K\in\psi_k^A} y_{k,t}^{AK} + \sum_{i\in\psi^F} y_{i,t}^{F} + \sum_{j\in\psi^R}\Big(y_{j,t}^{R0} + \sum_{J\in\psi_j^R} y_{j,t}^{RJ}\Big) = \sum_{i\in\psi^D\cup\psi^C} q_{i,t} \quad \forall t\in 1,\cdots T. \tag{33}$$

The whole proposed formulation is a mixed-integer linear programming problem. It is solved by optimization software CPLEX®.

IV. Simulation Results

A. Test System

The distribution network diagram and data can be found in [7]. The nodes 7, 10 and 13 are set as candidate places for building EV charging stations. All the data for the other nodes is the same as that given in [7], which is shown in Table I. The rated voltage of this system is 13.8kV and the allowable voltage range of each node is within [95%, 105%] of the rate voltage magnitude.

The planning horizon is four years, divided into three stages, the first two being one-year duration and the third being for two years. $\delta_1^{inv} = \delta_1^{oper} = 1$, $\delta_2^{inv} = \delta_2^{oper} = 0.9091$, $\delta_3^{inv} = 0.8264$, $\delta_3^{oper} = 1.5778$. The total charging capacity requirements are 1.2 MVA, 6.0 MVA and 8.4 MVA for each stage, respectively. Parameters of candidate charging stations are listed in Table II.

TABLE I
LOAD DATA OF THE TEST SYSTEM

Node number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Load /MVA	Stage 1	1.2	0	0	1.2	1.2	1.2	/	1.2	1.2	/	1.2	1.2	/	0	0	1.2
	Stage 2	1.2	1.2	1.2	1.2	1.2	1.2	/	1.2	1.2	/	2.4	1.2	/	1.2	1.2	1.2
	Stage 3	1.2	1.2	1.2	1.2	1.2	1.2	/	1.2	2.4	/	3.6	1.2	/	2.4	2.4	1.2

TABLE II
PARAMETERS OF CANDIDATE CHARGING STATIONS

Node number	Investment			Operational	Capacity/MVA	
	Fixed cost (new)/10^3\$	Fixed cost (expansion)/10^3\$	Variable cost/10^3\$/A	Cost/10^3\$/A	Min	Max
7	500	100	1	1	0.5	2
10	500	100	1	1	1	5
13	500	100	1	1	1	5

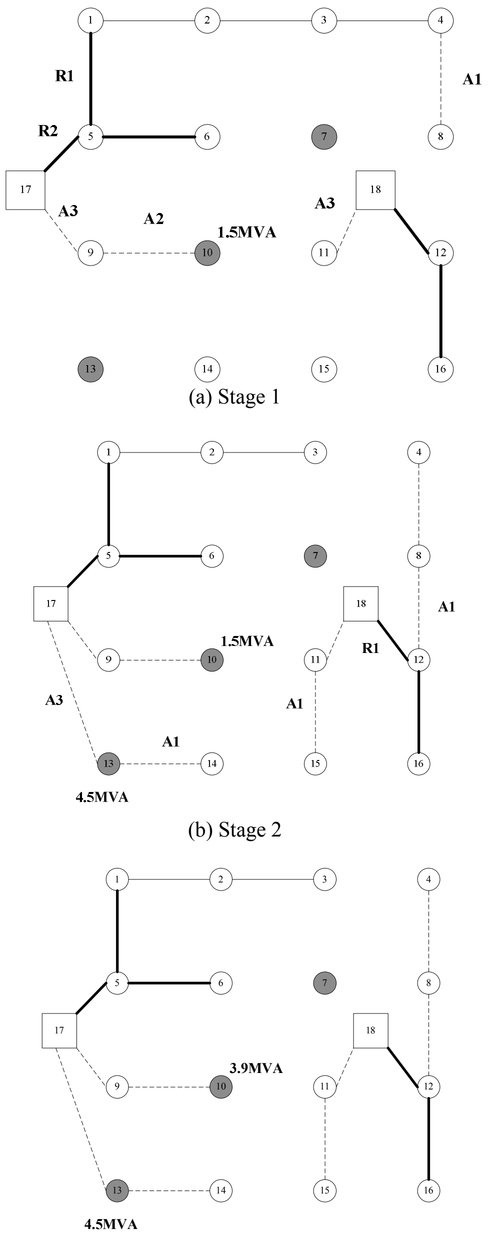
B. Results

The planning results are illustrated in Table III and Fig. 1. Totally, eight lines are built and three existing lines are replaced. The resulting network topology at each stage is strictly radial.

The demands and charging requirements are all satisfied. Only two charging stations are built to reduce the investment and operational costs. One charging station is built at stage 1 and expanded at stage 3. The other charging station is built at stage 2 and keeps unchanged at stage 3.

TABLE III
SUMMARY OF THE PROPOSED PLANNING RESULTS

Stage	Line built	Line replaced	Costs for network (10^3\$)	Charging capacity (MVA)			Charging station costs (10^3\$)	Total cost (10^3\$)
				Node 7	Node 10	Node 13		
1	4	2	993	0	1.5/new	0	717	
2	4	1	646	0	1.5	4.5/new	1146	4713
3	0	0	24	0	3.9/expansion	4.5	1187	



(c) Stage 3

Fig. 1. Single line diagram and charging station capacity of the solution at each stage

In order to show the merits of the multistage expansion method, the step by step planning method is simulated. The

planning result obtained at stage t-1 is set as the initial state of stage t. The corresponding planning results are given in Table IV and Fig. 2. Comparing the results obtained by the proposed method, the following differences should be noted although the final network topology is the same:

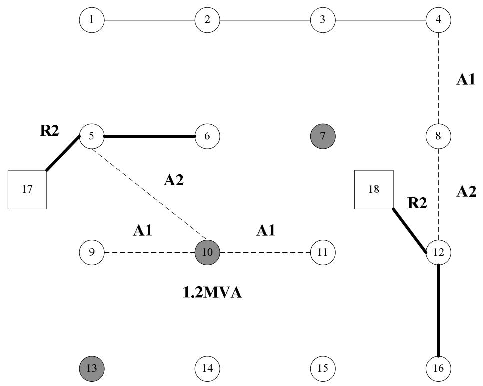
(1) The step by step method builds and replaces more lines than the proposed method (11 and six, respectively) because the planning results in each stage are not co-optimized. The line between node 5 and 10 added in stage 1 is discarded in the following stages. Two lines added in stage 2 (line 10-11 and 15-16) are not used in the final stage.

(2) The capacities of the resulting charging stations are different. The charging station at node 10 is expanded twice.

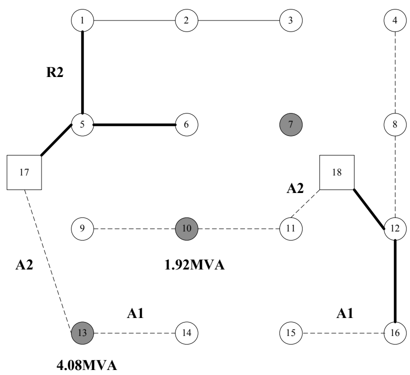
(3) The total cost of the planning result obtained by the proposed method is about 18% cheaper than that of the step by step planning method.

TABLE IV
RESULTS USING STEP BY STEP PLANNING METHOD

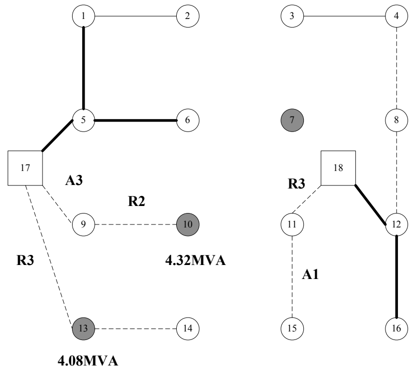
Stage	Line built	Line replaced	Costs for network (10^3\$)	Charging capacity (MVA)			Charging station costs (10^3\$)	Total cost (10^3\$)
				Node 7	Node 10	Node 13		
1	5	2	609	0	1.2/ new	0	674	
2	4	1	836	0	1.92/ expansion	4.08/new	1336	5555
3	2	3	471	0	4.32 expansion	4.08	1629	



(a) Stage 1



(b) Stage 2



(c) Stage 3

Fig. 2. Single line diagram and charging station capacity of the solution at the each stage using step by step planning method

In the above simulations, the total costs of building/expanding charging stations are higher than that of network expansion costs. Although the test data is not from practical projects, the costs of building charging facilities and the role of coordinated planning between distribution networks and charging facilities should not be neglected.

V. CONCLUSIONS

A mathematical formulation is proposed in this paper to solve distribution network expansion planning and optimal siting and sizing of EV charging station at the same time. A mixed-integer linear programming problem is built with comprehensive constraints considered, which includes the constraints of voltage magnitude limits and radial network topology requirement.

Simulations are carried out on the 18-node test system. Test results show that the proposed method can reduce the grid-connection cost of satisfying EV charging requirements. Comparisons show the superiority of the proposed multistage expansion planning method. More work is needed to put the method into practical use.

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